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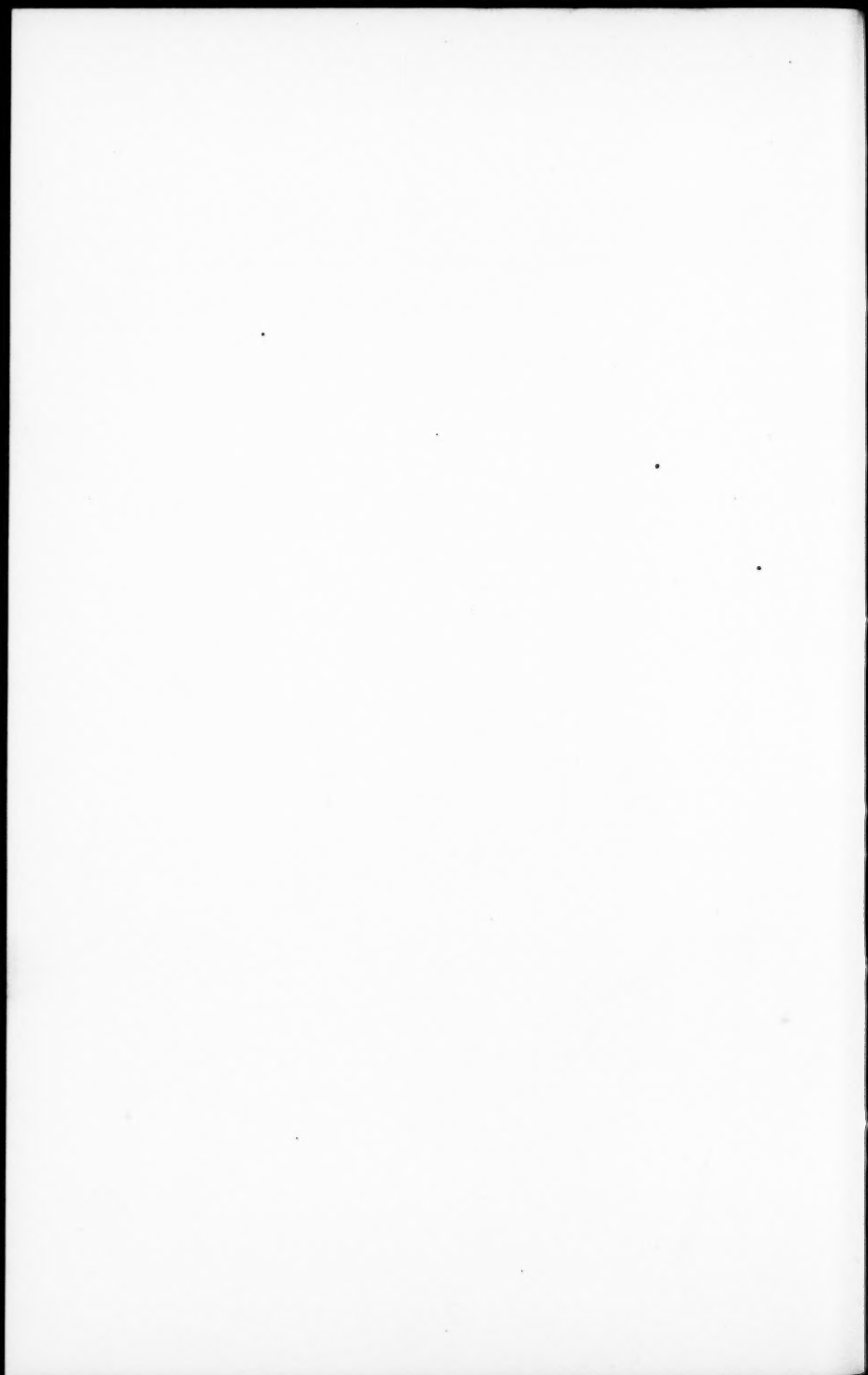
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COMPRESSIBILITY AND PRESSURE COEFFICIENT OF  
RESISTANCE, INCLUDING SINGLE CRYSTAL  
MAGNESIUM.

By P. W. BRIDGMAN.

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## INTRODUCTION.

DURING the last year measurements of compressibility have been extended to ten new materials; the effect of pressure on the electrical resistance of two of these has also been measured. The methods are the same as those already described in sufficient detail.<sup>1</sup> All of the materials described in this paper, except metallic magnesium, crystallize in the cubic system, so that measurements on crystalline aggregates give as much information as measurements on single crystals. Magnesium on the other hand, crystallizes in the hexagonal system; single crystals of this were prepared, the compressibility was measured parallel and perpendicular to the axis, and the specific resistance in the same directions was determined.

## DETAILED DATA.

*NaF.* The source of this material was powdered NaF from Kahlbaum. In order to get it into shape for the compressibility measurements it was compressed into a massive slug at a temperature of 580° C in an arbor press to a pressure of perhaps 10000 or 15000 kg/cm<sup>2</sup>. The specimen was only 0.28 cm. long, so that the relative accuracy of the results was less than usual. Regular measurements were made at 30° and 75°; the average arithmetical deviation of a single one of the 24 observed points from a smooth curve was 1.14% and 1.55% at 30° and 75° respectively. The following are the results calculated for the volume change from the measured change of length:

$$\left. \begin{aligned} \text{At } 30^\circ, \quad -\Delta V/V_0 &= 20.7 \times 10^{-7}p - 17.7 \times 10^{-12}p^2 \\ \text{At } 75^\circ, \quad -\Delta V/V_0 &= 20.8 \times 10^{-7}p - 18.1 \times 10^{-12}p^2 \end{aligned} \right\} p \text{ in kg/cm}^2.$$

*BaF<sub>2</sub>.* This was prepared in the same way as NaF, by compressing Kahlbaum's powdered BaF<sub>2</sub> at a temperature of 510° C in an arbor press. Attempts to melt it resulted in decomposition. The length of the slug so produced was about 2.1 cm. After the two compressibility runs the slug was found to be darkly discolored throughout the entire interior, and there was a permanent decrease of length of about 0.0025 cm. Whatever the nature of these effects, they were probably too small to materially affect the accuracy of the compressibility, which is known not to be sensitive to impurity.

At 30° the average departure from a smooth curve of a single one of the 14 readings was 0.64% of the maximum effect, and at 75° the average departure of a single one of the 13 readings, making one discard, was 0.49%. The following results for volume compressibility were calculated from the change of length:

$$\begin{aligned} \text{At } 30^\circ, \quad -\Delta V/V_0 &= 19.3 \times 10^{-7}p - 14.8 \times 10^{-12}p^2, \\ \text{At } 75^\circ, \quad -\Delta V/V_0 &= 19.6 \times 10^{-7}p - 14.6 \times 10^{-12}p^2. \end{aligned}$$

*SrF<sub>2</sub>.* This was prepared from Kahlbaum's powdered material by compressing at 580° in the arbor press. Two cylindrical pieces were made, 0.62 and 0.86 cm. long, which were piled together for measurement. There was no detectible change, either of length or appearance, produced in these specimens by the application of hydrostatic pressure. The average deviations from smooth curves of single readings at 30° and 75° were 0.70% and 0.83% on 14 and 12 readings respectively. The results for change of volume are:

$$\text{At } 30^\circ, \quad -\Delta V/V_0 = 15.8 \times 10^{-7}p - 10.3 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta V/V_0 = 16.1 \times 10^{-7}p - 10.8 \times 10^{-12}p^2.$$

*CdF<sub>2</sub>*. The material was powdered CdF<sub>2</sub> from Kahlbaum, compressed at 560° in the arbor press. It was, however, much more difficult to compact this into a uniform coherent mass, and a number of attempts had to be made. In order to get some idea of the possible error from imperfectly massive specimens, measurements were made on two different specimens. One of these was quite friable, and could easily be scratched to a powder with the point of a knife. The other was harder, and suggested no difficulties of a mechanical character. The length of the specimens was about 0.4 cm.; neither showed any appreciable change of dimensions after exposure to pressure. However, during the measurements on the softer specimen, there was an explosion due to the stem of the insulating plug blowing out, and after this there were large irregularities, so that apart from the softness of the specimen, the measurements with it could not be expected to be as good as those with the harder specimen. The compressibility calculated from the data obtained with the softer specimen was about 2.5% less than that with the harder specimen. The average deviations from smooth curves of single readings on the harder specimen were 1.2% and 0.9% at 30° and 75° respectively, on totals of 14 and 13 readings. The change of volume of the harder specimen was:

$$\text{At } 30^\circ, \quad -\Delta V/V_0 = 11.02 \times 10^{-7}p - 8.5 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta V/V_0 = 10.96 \times 10^{-7}p - 8.4 \times 10^{-12}p^2.$$

The temperature coefficient shown by these results is very uncertain. The results for either temperature by itself would not justify the four significant figures retained, which are given only to permit an estimate of the order of magnitude of the temperature effect.

*AlSb*. This intermetallic compound has been shown to be cubic by the measurements of Owen and Preston and of Goldschmidt.<sup>2</sup> The specimen was prepared for the compressibility measurements by fusing together in vacuum in a closed iron container weighed amounts of the pure metals, the antimony being Kahlbaum's purest, and the aluminum some specially pure material obtained from the Aluminum Co. of America which I had used in previous work.<sup>3</sup> In order to make the product as homogeneous as possible, it was heated and cooled several times. The specimen was about 1.5 cm. long. The grinding operation by which the specimen was fitted to the compressibility

apparatus was not as successful as usual, there probably being some rocking on the end pieces. In consequence the specimen could assume either one of two positions, so that the resulting points lay on two curves instead of one. This sort of behavior has been found before. There need be no error in the final results if enough measurements are taken to give a considerable number of points on both of the curves. At 30° 8 such points were obtained, and at 75° 12 pertaining to the same curve; the average departures of a single one of these points from a smooth curve was 0.64% and 0.48% respectively. The results for volume compressibility were as follows:

$$\text{At } 30^\circ, \quad -\Delta V/V_0 = 18.02 \times 10^{-7}p - 19.0 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta V/V_0 = 20.53 \times 10^{-7}p - 26.9 \times 10^{-12}p^2.$$

*CdTe.* This has also been shown by Zachariasen<sup>4</sup> to crystallize in the cubic system. It was prepared by melting together in a closed quartz tube weighed amounts of Kahlbaum's Cd and Te, the latter further purified by my method of making single crystals. The specimen, which was about 0.8 cm. long, showed, when mounted in the compressibility apparatus, to a slight extent the same positional instability as the AlSb, it being necessary to discard four of the observed points at 30°; at 75° none were discarded. There was a permanent decrease of length of 0.006 cm. after exposure to hydrostatic pressure; however, a seasoning application was made before the regular runs, so that no error should have been introduced by this effect. At 30° the average departure from a smooth curve of a single one of the 7 readings that were retained was 0.43% of the maximum effect, and at 75° the corresponding departure was 1.2% on 10 readings. The change of volume calculated from the results was:

$$\text{At } 30^\circ, \quad -\Delta V/V_0 = 23.3 \times 10^{-7}p - 12.2 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta V/V_0 = 23.5 \times 10^{-7}p - 11.6 \times 10^{-12}p^2.$$

*HgTe.* The measurements of Goldschmidt<sup>5</sup> have established that this also is cubic. It was prepared by heating together in a closed quartz tube weighed amounts of Kahlbaum's Te (the same as that used in preparing CdTe), and pure redistilled Hg from the laboratory stock. The specimen was about 1.1 cm. long; there was no perceptible change of length after exposure to pressure. The measurements on this material were more irregular than for any other substance, and in fact were so irregular that it was useless to try to get from them the

temperature coefficient of compressibility, but the observations at both temperatures were treated together to get from them the best single smooth curve. The average deviation from a smooth curve of a single one of the 26 observations was 2.1%. The following results were found for the volume compressibility:

$$\text{Mean, } 30^\circ \text{ and } 75^\circ, \quad -\Delta V/V_0 = 19.8 \times 10^{-7}p - 25 \times 10^{-12}p^2.$$

*TiN.* This material I owe to the kindness of Dr. van Arkel of the Philips Lamp Works, Eindhoven, Holland. It was prepared in the form of a slender rod about 1.0 mm. in diameter by the method of vacuum deposition which he has described.<sup>6</sup> The specimen was not a single grain, but the material is cubic, so that a single grain was not necessary.

*Compressibility.* The compressibility sample was 1.6 cm. long. Measurements were made as usual at  $30^\circ$  and  $75^\circ$ . This material is less compressible than iron, so that the slope of the curve was abnormal, and furthermore the effect is so small that no departure of the observed points from linearity could be established. At each temperature 13 observations were made; at  $30^\circ$  the average departure of a single point from a smooth curve was 1.2% and at  $75^\circ$  1.1%. The final results are:

$$\text{At } 30^\circ, \quad -\Delta V/V_0 = 3.32 \times 10^{-7}p - 2.13 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta V/V_0 = 3.51 \times 10^{-7}p - 2.13 \times 10^{-12}p^2.$$

The second degree term in these expressions is contributed by the absolute compressibility of the iron, there being no appreciable departure of the differential compressibility from linearity.

*Pressure Coefficient of Resistance.* The same specimen was used for the resistance and the compressibility measurements. The potentiometer method was used, connections being made by spring clips, since it is not possible to solder this material. In addition to measurements under pressure, the specific resistance and temperature coefficient of resistance were measured at atmospheric pressure. At  $30^\circ$  at atmospheric pressure the specific resistance was  $28.1 \times 10^{-6}$  ohms per cm. cube. The temperature coefficient at  $0^\circ$  C at atmospheric pressure, obtained by linear extrapolation of measurements at  $30^\circ$  and  $75^\circ$ , was 0.00221.

Pressure measurements were made as usual at  $30^\circ$  and  $75^\circ$ . The effect is unusually small; this, combined with the smallness of the absolute resistance of the specimen, made the percentage irregularity

in the results larger than usual. At  $30^\circ$  the average deviation from a straight line of a single one of the 11 readings was 1.2%, and at  $75^\circ$  the corresponding figure was 2.2% on 14 readings. The total displacement of the potentiometer slider for 12000 kg was 1 cm., so that an irregularity of 1% corresponds to 0.1 mm. setting of the slider, indicating that the readings were about as regular as the construction of the apparatus would allow. There was no appreciable departure from linearity at either temperature. The results follow:

Average coefficient to 12000 kg at  $30^\circ$ ,  $-9.35 \times 10^{-7}$ .

Average coefficient to 12000 kg at  $75^\circ$ ,  $-9.97 \times 10^{-7}$ .

The most important feature of the results is that the sign is negative, as it is for the majority of the pure metals.

*TiC.* This also I owe to the kindness of Dr. van Arkel. It was prepared by the same method as TiN; it also is cubic so that a single crystal was not necessary.

*Compressibility.* The sample was 2.5 cm. long, and 1.5 mm. in diameter; no perceptible alteration of dimensions as produced by pressure. This, like TiN, is less compressible than iron, and again it was not possible to detect any deviation from linearity of the observed differential compressibility. The average deviation from a straight line of a single one of the 13 observed points at  $30^\circ$  was 0.32%, and at  $75^\circ$  0.41% for 11 points. The results are:

At  $30^\circ$ ,  $-\Delta V/V_0 = 4.72 \times 10^{-7}p - 2.16 \times 10^{-12}p^2$ ,

At  $75^\circ$ ,  $-\Delta V/V_0 = 4.78 \times 10^{-7}p - 2.19 \times 10^{-12}p^2$ .

*Pressure Coefficient of Resistance.* The various details in measuring the resistance were the same as with TiN. The specific resistance at atmospheric pressure at  $30^\circ$  was found to be  $158.4 \times 10^{-6}$ . The temperature coefficient at atmospheric pressure at  $0^\circ$  C, by linear extrapolation of measurements at  $30^\circ$  and  $75^\circ$ , was  $+0.000235$ .

The pressure measurements showed no appreciable departure from linearity. At  $30^\circ$  the average departure from a smooth curve of a single one of the 15 readings was 1.3%, and at  $75^\circ$  the corresponding deviation was 0.7% on 14 readings. The results are:

Average coefficient to 12000 at  $30^\circ$ ,  $-1.375 \times 10^{-6}$ ,

Average coefficient to 12000 at  $75^\circ$ ,  $-1.35 \times 10^{-6}$ .



Again the coefficient is negative and about 50% larger numerically than for TiC. This is to be contrasted with a specific resistance 5.6 fold larger.

*Mg.* This material crystallizes in the hexagonal system, so that measurements, to be significant, must be made on single crystals. As far as I can find in the literature, single crystals of magnesium have not been hitherto studied. It proved, however, extremely easy to make this in single crystal form by my method of slow lowering of the molten metal from a furnace.<sup>7</sup> For this purpose a special vacuum furnace was constructed, in which a vacuum of the order of 0.01 mm. was maintained during operation. After many trials, iron crucibles were found to be by far the best.

*Compressibility.* For making the compressibility samples the crucible was about 2 cm. inside diameter and 7.5 cm. long, and was provided with a lid tightly clamped into position. The center of the lid was pierced with a fine steel tube, long enough to reach from the furnace to the colder parts of the enclosure; in this way the interior of the crucible could be exhausted, and at the same time the magnesium prevented from distilling out of the crucible, an effect which may be very annoying. The crucible was lowered at a rate of about 2 cm. per hour from a maximum temperature about 50° above the melting point. The magnesium with which the crucible was loaded was cut from a rod 4 cm. in diameter of commercially pure magnesium, which is usually very pure. The dimensions of the magnesium after casting into single crystal form were 2 cm. diameter and 5 cm. long. The crystal axis was located by optical examination of the reflection pattern. This was developed with unusual perfection, all 20 faces being present. These composed a band of 18 faces about the equator, 6 on the equator itself and 6 in a band on either side like the tropics of Cancer and Capricorn, and in addition 2 faces, one at each pole, perpendicular to the hexagonal axis. The crystal axis proved to make an angle of 51° with the length of the casting. Specimens for the compressibility measurements were cut from the casting with a jewellers saw, parallel and perpendicular to the axis. The following results were obtained.

*Parallel to the axis.* The length of the specimen was 2.0 cm.; there was no appreciable permanent deformation as a result of exposure to hydrostatic pressure. At 30° the average departure from a smooth curve of a single one of the 14 readings was 0.18% and at 75° 0.04% on the same number of readings. The greater regularity of these readings compared with that of the other materials of this paper is

what might be expected in view both of the greater geometrical perfection and more perfect homogeneity of the specimens. The numerical results were as follows:

$$\text{At } 30^\circ, \quad -\Delta l/l_0 = 9.842 \times 10^{-7}p - 6.51 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta l/l_0 = 10.154 \times 10^{-7}p - 7.78 \times 10^{-12}p^2.$$

*Perpendicular to the axis.* The length of this specimen also was 2.0 cm. and it showed no permanent distortion after exposure. At  $30^\circ$  the average departure from a smooth curve of a single one of the 14 readings was 0.08%, and at  $75^\circ$  0.15% on the same number. The numerical results are:

$$\text{At } 30^\circ, \quad -\Delta l/l_0 = 9.845 \times 10^{-7}p - 9.19 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta l/l_0 = 9.659 \times 10^{-7}p - 6.95 \times 10^{-12}p^2.$$

By combining these results for the linear changes, the following may be found for the volume compressibility:

$$\text{At } 30^\circ, \quad -\Delta V/V_0 = 29.53 \times 10^{-7}p - 28.3 \times 10^{-12}p^2,$$

$$\text{At } 75^\circ, \quad -\Delta V/V_0 = 29.47 \times 10^{-7}p - 24.7 \times 10^{-12}p^2.$$

I have previously measured the volume compressibility of a multi-crystalline extruded sample.<sup>8</sup> The results for this were: at  $30^\circ$ ,  $29.60 \times 10^{-7}p - 20.3 \times 10^{-12}p^2$ , and at  $75^\circ$ ,  $29.97 \times 10^{-7}p - 18.0 \times 10^{-12}p^2$ . The agreement is as good as could be expected in view of the indefinite character of the former sample.

*Electrical Resistance.* It was necessary to make special castings for the resistance measurements, since it would not have been possible without undue distortion to machine sufficiently slender rods out of the massive casting from which the compressibility samples were cut. The material was specially purified magnesium, which I owe to the kindness of Mr. R. S. Archer of the Research Laboratory of the Aluminum Co. of America. The new material was cast in the form of slender rods about 3 mm. in diameter and 5 cm. long in cylindrical iron molds; these molds were tightly closed at both ends. The rate of lowering from the furnace was about the same as for the larger casting. The mold was removed after casting by slitting with a fine saw in the milling machine. It was usually not possible to remove the mold without some slight bending of the specimen. However, the error so introduced was presumably small, as the resistance of this material does not seem sensitive to slight distortions. The orientation

of the rods was determined optically; the reflection patterns were not as fully developed as in the larger casting, but enough faces were always present to allow certain identification. Magnesium proved unexpectedly easy to get into single crystal form; none of the rods were multi-crystalline.

The specific resistance at  $22.5^\circ$  was obtained from potentiometer measurements of the resistance, combined with measurements of the

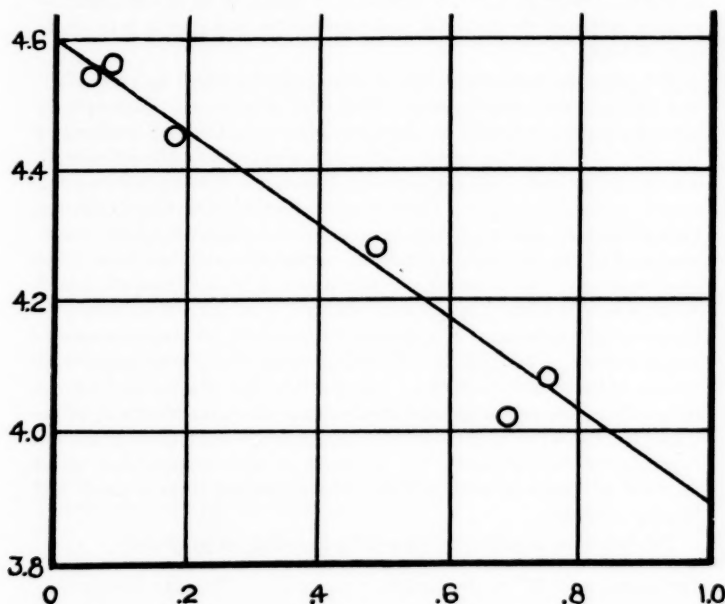


FIGURE 1. The specific resistance at  $22.5^\circ$  C of single crystal magnesium plotted against the square of the cosine of the angle between the hexagonal axis and the direction of current flow.

dimensions. The results are shown with sufficient accuracy in Figure 1, in which specific resistance is plotted against  $\cos^2 \theta$ , where  $\theta$  is the angle between the length of the rod and the hexagonal axis. Since there is no reason to suspect the correctness of the theoretical result that resistance is a linear function of  $\cos^2 \theta$ , the straight line drawn in

the figure may be taken as giving the most probable value of resistance. This means that the specific resistance perpendicular to the hexagonal axis is  $4.60 \times 10^{-6}$  and  $3.89 \times 10^{-6}$  parallel to it. The average specific resistance to be expected in a multi-crystalline casting is therefore  $4.36 \times 10^{-6}$ , or  $4.32 \times 10^{-6}$  corrected to  $20^\circ$ . This may be compared with the value  $4.46 \times 10^{-6}$  at  $20^\circ$  given in International Critical Tables for the polycrystalline metal. The new value is thus somewhat lower; part of this difference is probably to be explained by greater purity of the material, and part by the fact that it is in single crystal form.

The effect of pressure on the resistance up to  $12000 \text{ kg/cm}^2$  at  $30^\circ$  and  $75^\circ$ , and the temperature coefficient of resistance at atmospheric pressure, was determined on three samples, with the axes inclined at  $73^\circ$ ,  $30^\circ$ , and  $29^\circ$  to the length. The measurements on the  $30^\circ$  sample were irregular and could be used only to confirm in a general way the results on the  $29^\circ$  sample. There was considerable difficulty in obtaining satisfactory readings, both because of the smallness of the resistance and of the difficulty of making perfect electrical contact. The total resistance of the specimens was about  $2 \times 10^{-4}$ , and the maximum change produced by pressure about 5% of this. Consistency in the pressure readings to 1% demanded therefore resistance measurements correct to  $10^{-7}$  ohms. Electrical connections were made with springs of 0.010 inch piano wire snapped into fine grooves girdling the rods. Since the potentiometer method was used, no error was introduced by resistance at the contacts, but in order to allow high enough currents for measurement, the goodness of the contacts had to be restored at intervals with a high tension current from a small bell ringing magneto.

The following results were found for the effect of pressure:

Hexagonal axis  $73^\circ$  to the length,

$$\text{At } 30^\circ \text{ C, } -\frac{\Delta R}{R(0, 30^\circ)} = 5.61 \times 10^{-6}p - 8.4 \times 10^{-11}p^2.$$

$$\text{Average coefficient to } 12000 = -4.60 \times 10^{-6}.$$

$$\text{At } 75^\circ \text{ C, } -\frac{\Delta R}{R(0, 75^\circ)} = 5.67 \times 10^{-6}p - 8.35 \times 10^{-11}p^2.$$

$$\text{Average coefficient to } 12000 = -4.65 \times 10^{-6}.$$

Hexagonal axis  $29^\circ$  to the length,

$$\text{At } 30^\circ \text{ C, } -\frac{\Delta R}{R(0, 30^\circ)} = 5.48 \times 10^{-6} - 7.8 \times 10^{-11} p^2.$$

$$\text{Average coefficient to 12000} = -4.55 \times 10^{-6}.$$

$$\text{At } 75^\circ \text{ C, } -\frac{\Delta R}{R(0, 75^\circ)} = 5.99 \times 10^{-6} - 11.8 \times 10^{-11} p^2.$$

$$\text{Average coefficient to 12000} = -4.58 \times 10^{-6}.$$

The average departures of single readings from smooth curves were 1.2 and 1.5% for the  $73^\circ$  specimen, and 1.4 and 1.6% for the  $29^\circ$  specimen at  $30^\circ \text{ C}$  and  $75^\circ \text{ C}$  respectively. In comparing results for different specimens more emphasis should be placed on the average coefficients to 12000 than on the coefficients in the power series expansion.

The average pressure coefficient to 12000 of the polycrystalline metal to be calculated from the above, assuming the pressure coefficient is linear in  $\cos^2\theta$ , is  $4.58 \times 10^{-6}$ . This may be compared with my best previous value of  $4.07 \times 10^{-6}$  for magnesium of doubtless inferior purity. The direction of variation of pressure coefficient with increasing purity is the same as that always found hitherto, without exception.

The temperature coefficient at atmospheric pressure was obtained by linear extrapolation of the resistance at  $30^\circ$  and  $75^\circ$ . The following are the results:

Hexagonal axis  $73^\circ$  to the length,

$$\text{Mean coefficient } 0^\circ \text{ to } 100^\circ \text{ C, } 0.00439.$$

Hexagonal axis  $29^\circ$  to the length,

$$\text{Mean coefficient } 0^\circ \text{ to } 100^\circ \text{ C, } 0.00420.$$

The mean coefficient for polycrystalline metal, assuming the temperature coefficient to be linear in  $\cos^2\theta$ , demanded by these values, is 0.00432. The best previous observed value is apparently 0.00412.

#### DISCUSSION.

NaF was investigated chiefly because it was one of the substances which Slater<sup>10</sup> did not measure in his investigation of the compressi-

bility of the alkali halides, all in single crystal form. The specimen measured here was not a single crystal, but for a cubic crystal this is not important. The value for the compressibility of NaF found here fits smoothly into the series of values found by Slater. This is shown

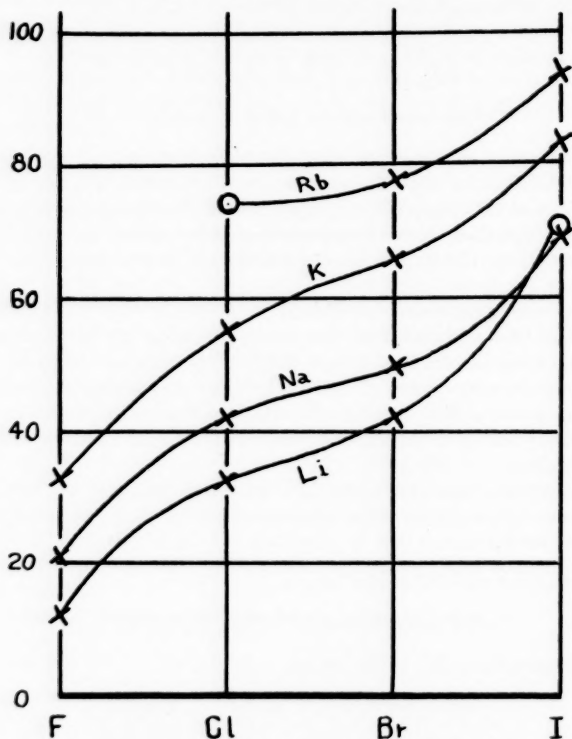


FIGURE 2. The compressibility at room temperature and atmospheric pressure of a number of the alkali halides. The curves connect the points for the compounds with the same alkali metal.

in Figure 2, in which the compressibilities at atmospheric pressure of various alkali halides are plotted with the successive halogens equispaced along the axis of abscissas. The two points for RbCl and LiI,

which lie distinctly off the curve, are taken from measurements of Richards and Saerens,<sup>11</sup> which were made by a different method. It would probably be worth while to repeat these measurements.

One might perhaps expect the same sequence of compressibilities on passing from one halogen compound to another in the series of the alkali earths as in the series of the alkali metals. That this is not the case is shown by Figure 3, in which are plotted the compressibilities found above for  $\text{BaF}_2$  and  $\text{SrF}_2$  together with the values found by Madelung and Fuchs<sup>12</sup> for  $\text{BaCl}_2$ ,  $\text{BaBr}_2$ ,  $\text{SrCl}_2$ , and  $\text{SrBr}_2$ . The

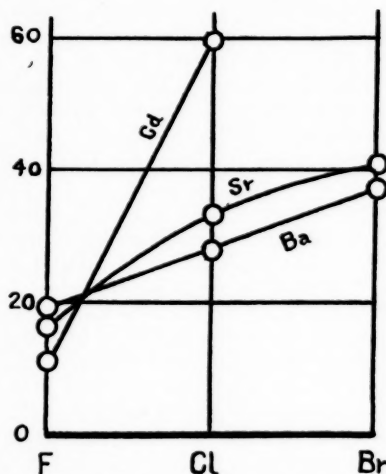


FIGURE 3. The compressibilities at atmospheric pressure and room temperature of the fluorides, chlorides and bromides of Sr and Ba, and the fluoride and chloride of Cd.

sequence is not maintained, but there is a reversal of order at fluorine as compared with chlorine and bromine. The data for  $\text{CdF}_2$  and  $\text{CdCl}_2$  are also plotted in the same diagram; here there is an enormous variation on passing from fluorine to chlorine, which almost might suggest that the crystal structures of these two compounds is not the same.

The compressibility of  $\text{AlSb}$  might perhaps be expected to be some sort of a mean between the compressibilities of its components. Per-

haps the most natural sort of a mean is one in which the compressibilities of the pure metals are weighted according to their atomic volumes. Taking the initial compressibility of Sb as  $27.0 \times 10^{-7}$  and its atomic volume as 18.2, with  $13.4 \times 10^{-7}$  and 10.0 as the corresponding figures for Al, the compressibility to be expected is

$$\left( \frac{18.2}{28.2} \times 27.0 + \frac{10.0}{28.2} \times 13.4 \right) \times 10^{-7} = 22.1 \times 10^{-7}.$$

The actual compressibility is  $18.0 \times 10^{-7}$ , 19% less. It is significant that the actual compressibility is less than that calculated; it is highly probable that at least part of this difference is to be explained by the effect of the internal cohesive pressure that the late Professor T. W. Richards was so fond of discussing. This cannot be the whole story, however, as is obvious from the non-cubical character of pure Sb and its greatly differing compressibility in different directions.

The compressibility of the two tellurides, CdTe and HgTe, differs even more from what may be calculated by the rule of mixtures. Taking the compressibilities of Te, Cd, and Hg (solid) as 50.8, 22.8, and  $33.1 \times 10^{-7}$ , and the corresponding atomic volumes as 21.2, 13.0, and 14.3, the calculated compressibility of CdTe is 40.1 and that of HgTe  $43.7 \times 10^{-7}$ , against the experimental values 23.3 and  $19.8 \times 10^{-7}$  respectively, which are thus about one-half the calculated values.

The low compressibilities of TiN and TiC is what would be expected from the high melting points and great mechanical hardness. Again the compressibility is very much less than that of the metallic constituent, the compressibility of pure Ti being about  $8 \times 10^{-7}$  against 3.3 for TiN and  $4.7 \times 10^{-7}$  for TiC. It is interesting that the compound with C is more compressible than that with N, although in the pure state solid N is much more compressible than C either as diamond or as graphite.

The electrical resistance of these two compounds puts them in the metallic class, the specific resistance of TiN being about 0.23, and that of TiC about 1.32 fold that of metallic Bi. The temperature coefficient of resistance of TiN, 0.00221, puts it not far from the pure metals; that of TiC, 0.00024, is in a different class. As far as the effect of pressure on resistance goes, the behavior is again in the class of the metals; the coefficient of TiN,  $-9.4 \times 10^{-7}$ , is not far from that of metallic Co, and the coefficient of TiC,  $-1.37 \times 10^{-6}$ , is not far from that of Mo. It would appear in general that the temperature coefficient of resistance is a more reliable criterion of the metallic character



of a substance than either the specific resistance or the pressure coefficient of resistance.

Magnesium is of interest because it is the first hexagonal metal measured in which the axial ratio corresponds to a piling of *spheres* in close packed hexagonal array. The piling in Zn and Cd, for example, is that of close packed ellipsoids. It is, of course, well known that the close packed hexagonal arrangement of spheres differs little from the close packed face centered cubic arrangement. In fact, if the two arrangements are built up by piling over each other layers perpendicular to the hexagonal axis, the only difference between the two arrangements is a slight relative displacement of the third layers, the first and second layers in the two arrangements being the same. Hence the forces on the atoms in the two arrangements can differ only by the contributions of the more distant atoms, which are unimportant because of the rapid falling off of atomic forces with increasing distance. It follows that a close packed hexagonal arrangement of spheres would not be expected to differ greatly in physical properties from a close packed cubical arrangement, and in particular, the compressibility of the hexagonal arrangement would be expected to be nearly the same parallel and perpendicular to the axis, because the compressibility of a cubic crystal has the same in all directions.

This expectation is strikingly borne out by the behavior of the compressibilities of magnesium; at  $30^\circ$  the initial compressibility in the two directions is practically the same. There are, however, small differences; the second degree terms differ, so that at high pressures magnesium is more compressible parallel to the axis than perpendicular. The temperature behavior in the two directions is also different; perpendicular to the axis the temperature coefficient of compressibility is negative, a rather unusual effect. Furthermore, the negative coefficient perpendicular to the axis more than compensates for the positive coefficient parallel to the axis, so that the initial temperature coefficient of volume compressibility is also negative. The second degree terms act differently, however, so that at high pressures the volume compressibility is greater at the higher temperature, as is normal.

The specific resistance of magnesium differs more in different directions than would be expected from the considerations above and from the fact that the compressibility is so nearly the same in all directions. Furthermore, the resistance is abnormal in that it is least parallel to the hexagonal axis, that is, the resistance is least for

flow across the basal plane. The only other example of this sort of behavior is antimony, and here the abnormality disappears at high pressures. The usually greater resistance across the basal plane is associated with the functioning of this plane as the plane of easiest slip or cleavage. The mechanical properties of single magnesium crystals have not yet been sufficiently studied to show whether in it the basal plane is also a slip plane or not.

After the manuscript of this article went to press, a paper has appeared by O. Sckell, *Ann. d. Phys.* 6, 932, 1930, in which it is shown that mercury (tetragonal) also has a smaller resistance parallel to the crystallographic axis.

The pressure coefficient of resistance does not vary as much with direction as does the specific resistance, but there is nevertheless a noticeable variation, and the variation is the same in character as that of the specific resistance, the pressure coefficient being least numerically in the direction in which the resistance is also least. It will be found on making the numerical calculation that the relative pressure coefficients are such in different directions that the ratio of resistance in the two principal directions is independent of pressure.

The temperature coefficient also varies with direction in the same way, the temperature coefficient being greatest in the direction in which the specific resistance is the greatest. The numerical values are such that the abnormal ratio of resistance in the two principal directions becomes accentuated at high temperatures.

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